Flying The Earth Observing Constellations

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1.0 The Earth Observing Constellations

NASA's Earth Science missions play a key role in the two international Earth Observing Constellations known as the Morning Constellation and the Afternoon Constellation. The science requirements to do coincidental observations have played a role in several missions' designs. The Earth observing constellations present operational challenges that had not previously been encountered. This paper takes a look at the on-orbit experience gained from the Morning Constellation and the planning being done for the Afternoon Constellation.

1.1 Definitions

In this paper, the term *constellation* refers to a group of satellites, which move in essentially the same/similar orbits and are distributed along this orbit in close proximity such that they over-fly the same geographic regions within seconds (to minutes) of each other. All of the satellites have approximately the same mean orbital elements, that is, they have their respective semi-major axis, eccentricity, and argument of perigee matched very closely in value. The right ascension of the node and the mean anomaly are approximately matched, but less so than the other elements.

The term *formation* is often confused with constellation flying. *Formation flying* refers to two or more satellites moving in similar orbits and where their control boxes are relative to one and another and positioned in close, along-track proximity for the purpose of making coordinated, co-registered observations of the same geographical locations within a few seconds. Satellites in formation require active control by at least one of the satellites in order to preserve the formation. Because of the close proximity of the satellites and the requirements for tight control, formation flying requires the exchange of orbital ephemeris data between members of the formation.

2.0 Morning Constellation

Prior to the launch of the Landsat-7 and the Earth Observing System (EOS) Terra satellites in 1999, the Project Scientists for the two missions and the Earth Science Data and Information System (ESDIS) Project at NASA's Goddard Space Flight Center signed an inter-project agreement document describing their plan to fly in loose formation within approximately 20 minutes each other, with the Landsat-7 mean local time (MLT) at the equator crossing at 10:00 a.m. and the Terra MLT at 10:15 ±15 minutes.

In November 2000, a technology demonstration satellite, Earth Observer-1 (EO-1), was launched into the same orbit as that of Landsat-7 and Terra, with a goal of flying in formation within one minute from Landsat-7. The SAC-C satellite, developed and operated by the Argentine Space Agency, the Comision Nacional de Actividades Espaciales (CONAE), was launched along with EO-1 and also planned to fly near both Terra and Landsat-7.

These on-orbit placements enable the scientists to make use of the scientific synergy among the instruments on the different spacecraft. This group of four satellites constitutes the morning constellation, led by the Landsat-7.

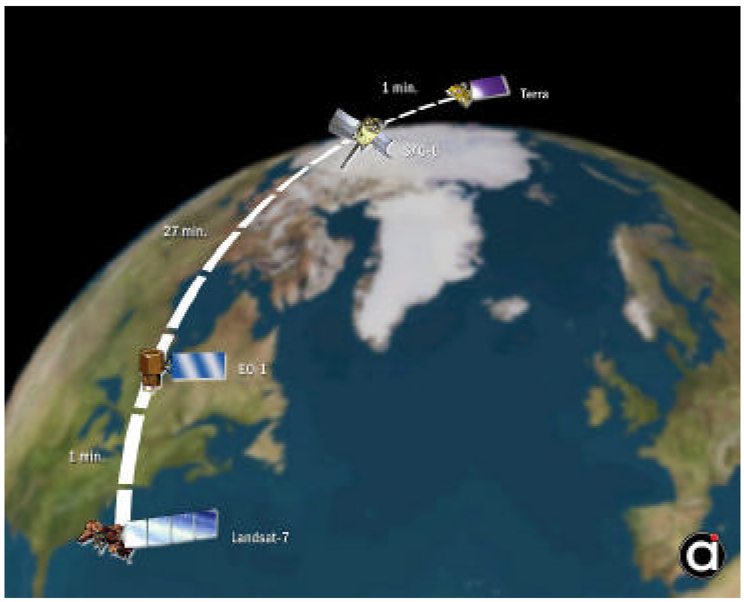
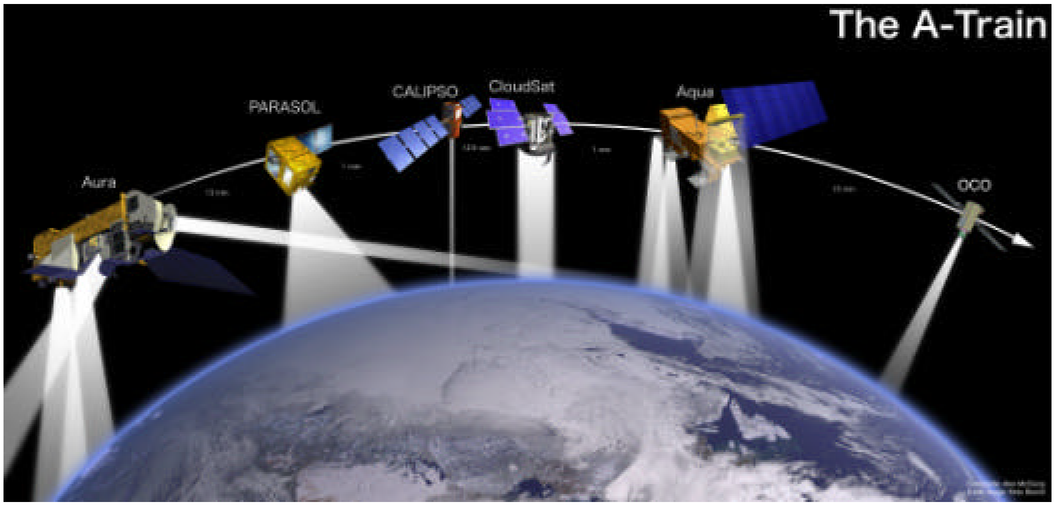


Figure 1. Morning Constellation

3.0 Afternoon Constellation

In May 2002, the EOS Aqua satellite was launched into an orbit with an altitude of 705 km. and a 1:30 p.m. MLT (Figure 2). This year, the Aura satellite will be launched and phased in relation to the Aqua satellite, such that the instruments on Aura will be able to view the same mass of air no later than 8 minutes after the instruments on Aqua have observed it. Two smaller satellites, CALIPSO (a joint U.S./French mission) and CloudSat (a joint NASA/Colorado State University/Air Force mission) plan to fly in tight formation within 15 seconds of each other; they also plan to be within 30 to 60 seconds of the Aqua satellite. The PARASOL satellite, managed by the French Space Agency, Centre National d'Etudes Spatiales (CNES), will be launched and placed within one minute of the CALIPSO satellite. The OCO satellite will be launched in 2007 and will be stationed approximately 15 ahead of Aqua. Representatives from each mission are presently developing agreements and procedures in order to coordinate on-orbit operations.



Note: All time differences refer to equator crossing times (not MLTs).

Figure 2. Afternoon Constellation

4.0 Science Requirements and Mission Design

Why are all these satellites planning to fly as part of a constellation? The answer is that as a constellation, the scientists will be able to acquire science data not only from their specific instruments on a single satellite, but science data from the other satellites which will have been taken at approximately the same time, thus resulting in coordinated science observation data. Combining the information from several sources gives a more complete answer to many questions than would be possible from any single satellite. This leads to better quality science.

The Morning Constellation (Table 1) sensors consist mainly of instruments directed at observing important aspects of the physical climate system, the carbon cycle, and atmospheric chemistry. Terra, the first EOS platform, is especially focused on the first two. The Landsat Enhanced Thematic Mapper (ETM+) is a higher spatial resolution sensor that provides imagery containing detailed information necessary to interpret Terra data into useful parameters over the land surface, as well as the lead instrument for studying land cover and land use change. Landsat-7 contributions are in the areas of land surface parameter scale-integration and validation, monitoring of land cover changes, vegetation classification, and radiometric rectification. These benefits increase as the Terra and ETM+ observations are brought closer together on orbit because Terra data can then be used to atmospherically correct Landsat images for the effects of aerosols and atmospheric water vapor (in addition to simplifying other data processing tasks). EO-1 is a technology demonstration mission with sensors on-board that represent those anticipated for future land imaging missions. EO-1 images provide a way to validate image data from Landsat-7. SAC-C is designed to provide high-resolution videography and moderate resolution multi-spectral scanner imagery of land and ocean surfaces. Several years on orbit have provided some interesting results from the Morning Constellation.

Table 1. Morning Constellation Summary

Spacecraft	Summary Of Mission	Instruments	Launch Date	Responsible Organization
Landsat-7	Gathers remotely sensed images of the land surface and surrounding coastal regions for global change research, regional environmental change studies and other civil and commercial purposes	ETM+	Dec 1999	USGS
EO-1	Demonstrates advanced land imaging instruments and high payoff spacecraft technologies	ALI Hyperion LEISA/AC	Nov 2000	NASA/GSFC
SAC-C	Provide multispectral imaging of terrestrial and coastal environments. Studies the structure and dynamics of the Earth's atmosphere, ionosphere and geomagnetic field. Seeks to measure the space radiation in the environment and its influence on advanced electronic components. Determines migration route of the Franca whale. Verifies autonomous methods of attitude and orbit determination.	MMRS Whale Tracker HSTC GOLPE MMP ICARE	Nov 2000	CONAE
Terra	Studies land cover and land use change, seasonal-to-interannual climate variability, natural hazards research and applications, long-term climate natural variability and change, and atmospheric ozone	ASTER CERES MISR MODIS MOPITT	Dec 1999	NASA/GSFC

Note: See Acronyms section at end of this paper for acronym expansions

The science teams on the Afternoon Constellation missions that follow EOS Aqua have a requirement to take advantage of the Aqua instrument data acquired at almost the same time as their instruments (Table 2) . For example, aerosol height information obtained by CALIOP (on CALIPSO) will be combined with data on aerosol size distribution and composition obtained by POLDER (on PARASOL) and MODIS (on Aqua). CALIOP also provides additional information on aerosol shape and a qualitative classification of aerosol size; data from OMI (on Aura) will provide information on the global distribution of absorbing aerosols. These observations will be compared to global emission and transport models -- data from CALIOP, POLDER, MODIS and OMI will all help answer this question. Data from CERES is crucial for providing information on earth radiation budget. Data from AIRS, HSB and AMSR-E will provide information on how aerosol climate forcing changes with atmospheric humidity. Information from these sensors can also be used in conjunction with data from CloudSat's Cloud Profiling Radar (CPR) to offer an unprecedented opportunity to understand what role aerosols play in changing cloud properties, and thus changing the earth radiation budget. Information from CALIOP, CPR, HSB, AMSR-E, and MLS will be combined to produce vertical profiles of cloud systems. Combining information from CPR, CALIOP, and POLDER is expected to shed light on the nature of mixed phase clouds (clouds composed of both water and ice) and help improve parameterizations of these processes in atmospheric models.

Table 2. Afternoon Constellation Summary

Spacecraft	Summary Of Mission	Instruments	Launch Date	Responsible Organization
Aqua	Synergistic instrument package studies water in the Earth/atmosphere system, including its solid, liquid and gaseous forms.	AIRS/AMSU-A/HSB AMSR-E CERES MODIS	May 2002	NASA/GSFC
Aura	Study the horizontal and vertical distribution of key atmospheric pollutants and greenhouse gases and how these distributions evolve and change with time.	HIRDLS MLS OMI TES	June 2004	NASA/GSFC
CALIPSO	Observations from space-borne lidar, combined with passive imagery, will lead to improved understanding of the role aerosols and clouds play in regulating the Earth's climate.	CALIOP IIR WFC	March 2005	NASA/GSFC NASA/LaRC CNES
CloudSat	Cloud Profiling Radar will allow for most detailed study of clouds to date and should better characterize the role clouds play in regulating the Earth's climate.	CPR	March 2005	NASA/GSFC NASA/JPL
PARASOL	Polarized light measurements will allow better characterization of clouds and aerosols in the Earth's atmosphere.	POLDER	2004	CNES
OCO	Will make global, space-based observations of the column integrated concentration of CO_2, a critical greenhouse gas.	Three grating spectrometers	2007	NASA/GSFC NASA/JPL

Note: See Acronyms section at end of this paper for acronym expansions

5.0 Operations Coordination: Morning Constellation On-orbit Realities

Prior to launch, Landsat-7's goal was an orbit with a 10:00 a.m. MLT crossing time; Terra's baseline requirement was 10:30 ±15 min. Landsat-7's launch and ascent went nominally and the desired orbit was achieved. Terra's launch however was delayed until the end of its window, plus orbit ascent maneuvers were delayed by an attitude control anomaly, resulting in a beginning-of-life MLT of 10:47 a.m., significantly later than planned and outside of mission requirements. Consequently, a series of Terra burns were performed to attain an earlier MLT (~10:32 a.m.).

SAC-C's inclination was planned such that its MLT would drift from 10:16 a.m. to a mid-mission maximum near 10:30 a.m., and then decrease. The original constellation goal was for Terra to trail Landsat-7 by 15-20 minutes. To meet this goal, Terra would need to pass SAC-C. Analysis showed however that the Terra and SAC-C orbits would cross in April 2002 and that a safe orbit passing was *not* possible without Terra leaving the Worldwide Reference System (WRS)-2 grid and thus violating its mission orbit requirements. In the end, Terra performed six inclination maneuvers to raise its inclination to match SAC-C's (Figure 3) and will perform yearly inclination maneuvers to maintain a safe MLT near 10:30 a.m. (SAC-C does not perform any maneuvers).

Coordination is required for ground track control maintenance maneuvers to keep EO-1 in tight formation with Landsat-7. EO-1 plays "follow the leader" with Landsat-7; the latter targets its ground track control burns for Tuesdays, enabling EO-1 to burn on Thursdays. With inclination burns, EO-1 originally planned to wait until Landsat-7 completed their inclination burns before performing their own burns. Experience has changed this so that EO-1 now performs 1/2 of its burn prior to the Landsat-7's, and then completes the remaining 1/2 of its burn after the Landsat-7 burn is complete.

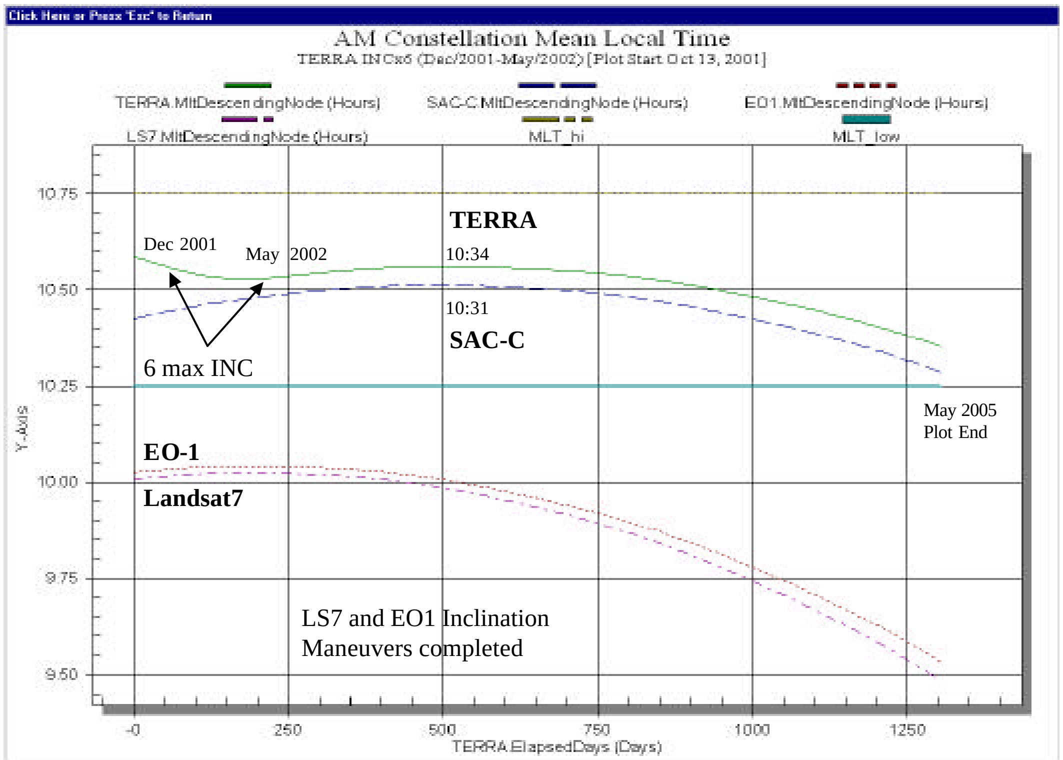


Figure 3. Morning Constellation Mean Local Time (MLT) Relationships

As a group, the Morning Constellation scientists meet periodically to discuss science results. The operations teams of the various satellites documented their agreements in the "Morning Train Coincident Observation Implementation and Operations Plan", dated September 2002. They coordinate via telecon, as needed.

6.0 Afternoon Constellation Operations Coordination

Learning from the Morning Constellation operations experience, NASA/GSFC formed an Afternoon Constellation Mission Operations Working Group (MOWG) in 2002 to address the operations coordination and planning for the Afternoon constellation. The group consists of representatives from the science and operations teams of the member missions.

Constellation safety is a primary concern due to the close proximity of some of the missions. Routine monitoring of the Afternoon Constellation is necessary to ensure the safety of all member satellites. The monitoring is based on the concept of *control boxes* (i.e., regions defining the limits of a satellite's allowable motion) and regular inputs (such as orbit data and maneuver plans) from each of the mission operations teams to a centralized system developed by the Earth Science Mission Operations (ESMO) Project called the Constellation Coordination System (CCS). When satellites are performing nominally, minimal coordination is required. But, when this is not the case (e.g., when a satellite is in safe-hold and/or may have lost the ability to maneuver), the affected member satellites must coordinate their efforts to avoid potentially dangerous situations. Some examples follow.

- *Close approaches due to planned maneuvers*: In nominal operations, a close approach is unlikely if the satellites stay in their individual control boxes. CloudSat and CALIPSO represent an exception since they share a control box; these two missions require extra diligence to ensure no close approaches occur.
- *Close approaches due to spacecraft anomalies*: If a satellite experiences an incapacitating failure that prevents it from maneuvering, it may drift and present a close approach risk to other member satellites in the Afternoon Constellation. A *failed* maneuver attempt may also cause one satellite to leave its control box and approach another satellite.
- *Planning maneuvers that affect multiple Afternoon Constellation members*: One satellite's maneuver may need to be coordinated with other mission teams. For example, if Aqua has to perform an inclination maneuver, the other Afternoon Constellation members must follow suit in order to maintain the constellation configuration. The timing of the maneuvers needs to be coordinated with all affected missions to prevent conflicts.

Agreements must be in place to resolve constellation conflicts. Normally, affected mission teams will resolve conflicts directly, but when this proves unfeasible, a documented, binding process must be followed that elevates unresolved issues to a higher level, namely a Constellation Executive Board (Figure 4). If necessary, issues that are still outstanding can be passed even further to NASA Headquarters and CNES Headquarters for resolution.

Summary

Safety is a prime consideration when flying constellations. Long before missions are approved to fly as a mission and as part of a constellation, the operational aspects must be thoroughly evaluated to assure the safety of the constellation missions and to minimize the risks associated with constellation flying. Also, by addressing what needs to be implemented in the space and ground systems to meet coincidental observation requirements, operational work-arounds can be minimized and thus, reduce the cost of long term mission operations and enable quality science. Pre-launch and on-orbit coordination among missions is absolutely necessary. Operations coordination plans and agreements (including a conflict resolution process) need to be in place prior to getting on orbit.

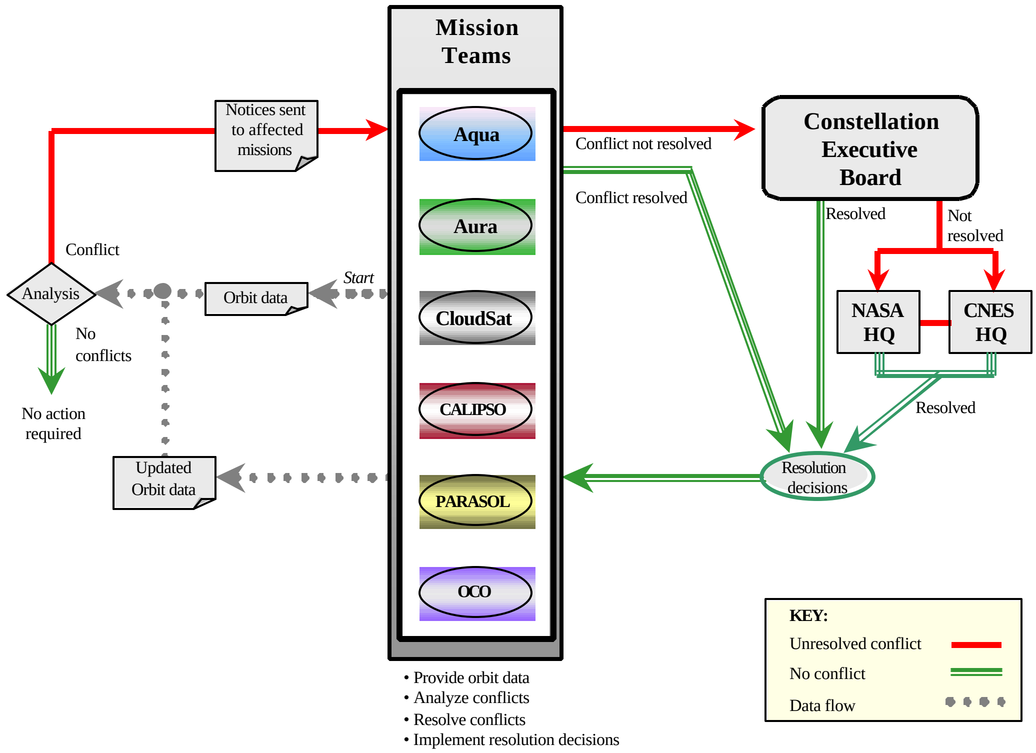


Figure 4. Afternoon Constellation Coordination

Acknowledgements

The paper reflects discussions with the Morning and Afternoon Constellation teams. Special thanks also go to Kevin Work/EOS, Seth Shulman/EO-1, and Ed Macie for lessons learned from the Morning Constellation and to Ed Hanka for his support in developing the Afternoon Constellation Implementation Plan.

Abbreviations and Acronyms

AIRS	Atmospheric Infrared Sounder
ALI	Advanced Land Imager
AMSU	Advanced Microwave Sounding Unit
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCS	Constellation Coordination System
CERES	Clouds and the Earth's Radiant Energy System
CNES	Centre National d'Etudes Spatiales
CONAE	Comision Nacional de Actividades Espaciales
CPR	Cloud Profiling Radar
EO-1	Earth Observer-1
EOS	Earth Observing System
ESDIS	Earth Science Data and Information System
ESMO	Earth Science Mission Operations
ETM	Enhanced Thematic Mapper
GOLPE	Global Positioning System (GPS) Occultation and Passive Reflection Experiment
GSFC	Goddard Space Flight Center
HIRDLS	High Resolution Dynamics Limb Sounder
HSB	Humidity Sounder for Brazil
HSTC	High Sensitivity Technological Camera
ICARE	Influence of Space Radiation on Advance Components
IIR	Imaging Infrared Radiometer
INC	inclination
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center
LEISA/AC	Linear Etalon Imaging Spectrometer Array/Atmospheric Corrector
MLS	Microwave Limb Sounder
MLT	mean local time (of equator crossing)
MMP	Magnetic Mapping Payload
MMRS	Multispectral Medium Resolution Scanner
MODIS	Moderate Resolution Imaging Spectroradiometer
MOWG	Mission Operations Working Group
NASA	National Aeronautics and Space Administration
OCO	Orbiting Carbon Observatory
OMI	Ozone Monitoring Instrument
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a LIDAR
POLDER	Polarization and Directionality of the Earth's Reflectances
SAC-C	Satelite de Aplicanciones Cientificas-C
TES	Tropospheric Emission Spectrometer
WFC	Wide Field Camera
WRS	Worldwide Reference System